Supporting Information for "The energy budgets of giant impacts"

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Introduction

This document details the supporting information for the article titled "The energy budgets of giant impacts". It contains text describing a scaling relation for internal energy gain in 'Earth-sized' giant impacts and an accompanying figure, a table summarizing the relevant results of the SPH impact simulations described in the aforementioned article, and eight animations that show the time evolution of the example impacts discussed throughout the article. The remaining sections of this document contain the supplementary text, and figure and the captions for these supporting information files.

S1 Internal energy increase scaling relation

As discussed in the article, Figure 6 shows the increase in internal energy resulting from giant impacts as a function of modified specific impact energy. A mass ratio dependence in the energy gain is clear. We found that these data could be collapsed further using the same mass ratio correction as found for the catastrophic disruption criterion by Leinhardt and Stewart (2012). Figure S1 shows the internal energy gain in giant impacts that produce approximately Earth-mass bodies as a function of a modified kinetic energy: $K\,(1-b)\,\gamma/(\gamma+1)^2$, where b is the impact parameter, γ is the projectile-to-target mass ratio, and K is the kinetic energy of the impact defined according to: $K = 0.5\,\mu v_{\mathrm{i}}^2$, where μ is the reduced mass, $\mu = mM/M_{\mathrm{tot}}$; and v_{i} is the impact velocity in the centre of mass frame. We find a reasonable fit to the internal energy gain with a simple power law, though the physical interpretation is unclear. We stress that there are a variety of acceptable fits, and the power law index can be varied by ± 0.05 and give a similarly acceptable fit. The internal energy gain, ΔE_{int}, in giant impacts that produce approximately Earth-mass bodies can be found via the scaling relation:

$$\Delta E_{\mathrm{int}} \simeq 5.84 \times 10^{-4} \left[K(1-b)\frac{\gamma}{(\gamma+1)^2} \right]^{0.1} - 0.93. \tag{S1}$$

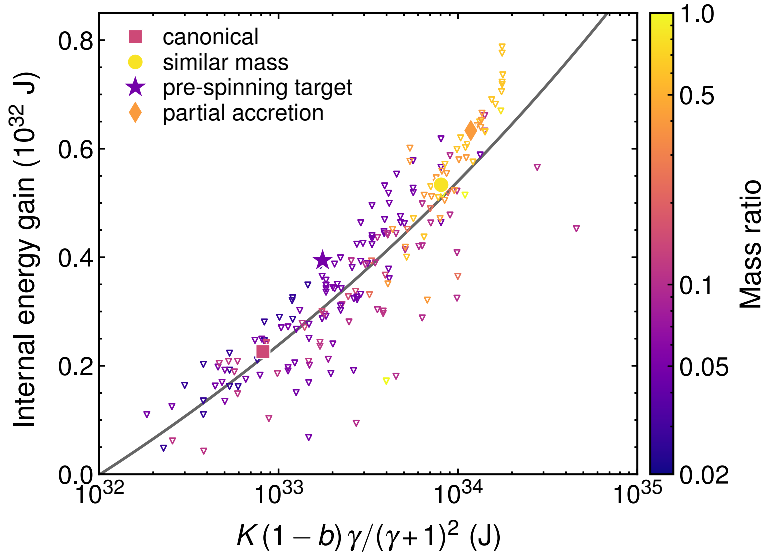

Figure S1. Internal energy gain of the system at 24 hours after the impact as a function of modified kinetic energy. The grey line is the scaling relationship given in equation S1. The colours of the points indicate the ratio of projectile to target mass. The four example impacts shown throughout this work are indicated by unique symbols.

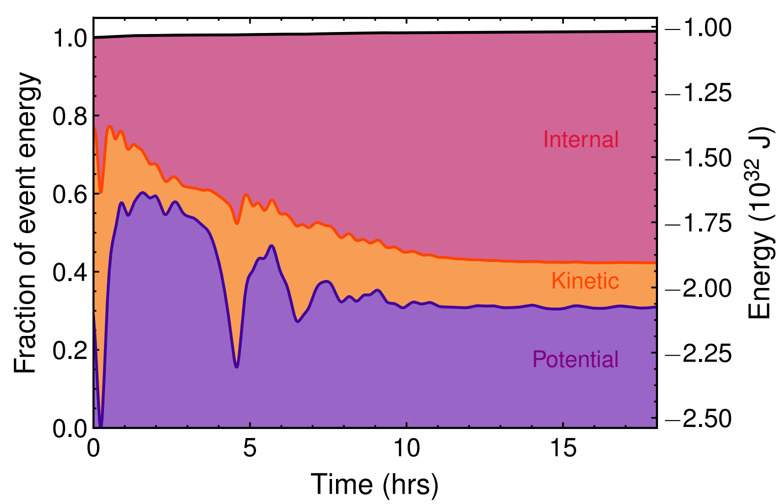

Figure S2. Energy budget of a similar mass impactor scenario similar to M0572p0M468p0v9.7b0.55 shown in the main article calculated using the new and more densely-gridded EOS tables from Stewart et al. (2019). The energy budget is the sum of the participating potential energy, kinetic energy and internal energy. Compare to Panel *b* of Figure 4. In this case the bound material is not plotted separately but included in total. The energy conservation is significantly improved over the version shown in the article, while the phenomenology remains extremely similar.

Table S1. Summary of impact simulations discussed in this work. Label is the simulation identification label; M ($M_\oplus$), R (km), N, L (L_{EM}), W (rad s^{-1}) are the mass, radius, number of SPH particles, spin angular momentum and angular velocity of the target; m, r, n, l, w are the mass, radius, number of SPH particles, spin angular momentum and angular velocity of the projectile; v (km s^{-1}), b, Qs (J kg^{-1}) are the velocity, impact parameter and specific energy of the impact; PE_0 (J), PE_min, PE_24 are the gravitational potential energy at the start of the simulation, at potential minimum and at 24 hours; KE_0 (J), KE_24, IE_0, IE_24 are the initial and 24 hour kinetic and internal energies; and EOSflag indicates whether the simulation used the original forsterite table (o) or the more finely gridded version (f).

Movie S1. Midplane SPH density (top left), near-midplane SPH particle locations where blue particles represent silicate mantle and orange particles represent iron core (bottom left), and energy budget using the participating potential energy (right) for the example canonical Moon-forming impact. The number in the top right corner of the bottom left panel is the time in hours since the start of the simulation. The density is shown using a Delaunay triangulation interpolation, where black regions have densities below the miniumum of the color scale. The images in the left hand panels are recentered on the gravitational potential minimum of the system.

Movie S2. Midplane SPH density (top left), near-midplane SPH particle locations where blue particles represent silicate mantle and orange particles represent iron core (bottom left), and energy budget using the participating potential energy (right) for the similar mass impactors example. The number in the top right corner of the bottom left panel is the time in hours since the start of the simulation. The density is shown using a Delaunay triangulation interpolation, where black regions have densities below the miniumum of the color scale. The images in the left hand panels are recentered on the gravitational potential minimum of the system.

Movie S3. Midplane SPH density (top left), near-midplane SPH particle locations where blue particles represent silicate mantle and orange particles represent iron core (bottom left), and energy budget using the participating potential energy (right) for the example pre-spinning proto-Earth impact. The number in the top right corner of the bottom left panel is the time in hours since the start of the simulation. The density is shown using a Delaunay triangulation interpolation, where black regions have densities below the miniumum of the color scale. The images in the left hand panels are recentered on the gravitational potential minimum of the system.

Movie S4. Midplane SPH density (top left), near-midplane SPH particle locations where blue particles represent silicate mantle and orange particles represent iron core (bottom left), and energy budget using the participating potential energy (right) for the example partial accretion impact. The number in the top right corner of the bottom left panel is the time in hours since the start of the simulation. The density is shown using a Delaunay triangulation interpolation, where black regions have densities below the miniumum of the color scale. The images in the left hand panels are recentered on the gravitational potential minimum of the system.

Movie S5. Midplane specific entropy for the example canonical impact. The number in the top right corner of the panel indicates the time in hours since the start of the simulation. The color scale indicates the entropy of the material, and transparency indicates the density, where the lowest density material is almost entirely transparent. A Delaunay triangulation interpolation has been used to calculate the properties of the materials at all locations. The images are recentered on the gravitational potential minimum of the system.

Movie S6. Midplane specific entropy for the similar mass impactors example. The number in the top right corner of the panel indicates the time in hours since the start of the simulation. The color scale indicates the entropy of the material, and transparency indicates the density, where the lowest density material is almost entirely transparent. A Delaunay triangulation interpolation has been used to calculate the properties of the materials at all locations. The images are recentered on the gravitational potential minimum of the system.

Movie S7. Midplane specific entropy for the example pre-spinning proto-Earth impact. The number in the top right corner of the panel indicates the time in hours since the start of the simulation. The color scale indicates the entropy of the material, and transparency indicates the density, where the lowest density material is almost entirely transparent. A Delaunay triangulation interpolation has been used to calculate the properties of the materials at all locations. The images are recentered on the gravitational potential minimum of the system.

Movie S8. Midplane specific entropy for the example partial accretion impact. The number in the top right corner of the panel indicates the time in hours since the start of the simulation. The color scale indicates the entropy of the material, and transparency indicates the density, where the lowest density material is almost entirely transparent. A Delaunay triangulation interpolation has been used to calculate the properties of the materials at all locations. The images are recentered on the gravitational potential minimum of the system.

References

Leinhardt, Z. M., & Stewart, S. T. (2012, January). Collisions between Gravity-dominated Bodies. I. Outcome Regimes and Scaling Laws. ApJ, *745*, 79. doi: 10.1088/0004-637X/745/1/79

Stewart, S. T., Davies, E. J., Duncan, M., Lock, S., Root, S., Townsend, J., ... Jacobsen, S. (2019, October). The shock physics of giant impacts: Key requirements for the equations of state. In *Aip conference proceedings, sccm19.* (in revision. https://arxiv.org/abs/1910.04687)